Correlation between Spectral Parameters of Acoustic Emission during Plastic Deformation of Cu and Cu-Al Single and Polycrystals

A. Vinogradov*, M. Nadtochiy**, S. Hashimoto* and S. Miura*

*Department of Engineering Physics and Mechanics, Kyoto University, Kyoto 606-01, Japan

**Department of Physics, Togliatti Polytechnic Institute, Togliatti 445667, Russia

A number of spectral parameters of acoustic emission measured on copper and copper-aluminum single and polycrystals have been analyzed with the aim to establish the mutual correlations between them. It has been shown that since there are no simple correlations between most of the AE spectral parameters, it is necessary to consider a set of certain parameters to the realistic characterization of spectrum as a whole. The minimum set recommended includes the maximum power (energy) density, central frequency, effective width of spectrum or median frequency and total power (energy).

(Received August 8, 1994)

Keywords: acoustic emission, spectral analysis, single crystals, polycrystals

I. Introduction

There have been a number of investigations into the spectral features of acoustic emission (AE)⁽¹⁾⁻⁽⁶⁾. Numerous parameters have been used for a quantitative description of AE spectra for both continuous and burst emission. Among these are a power spectral density⁽¹⁾⁻⁽⁸⁾, median frequency⁽⁶⁾, total AE energy and central frequency. In addition, some parameters of AE pulses such as peak amplitude, root mean square voltage⁽⁹⁾, AE activity (the number of pulses per unit time), intensity (the number of counts per unit time)⁽¹⁰⁾, rise time, etc., are frequently used with the aim of defining the most "informative" AE parameter reflecting the features of local structural transformations. AE was studied in the single crystals of copper⁽¹⁾⁽²⁾, aluminum⁽⁷⁾, copper-aluminum alloys⁽¹⁾, zinc⁽⁹⁾, molybdenum and tungsten⁽¹⁰⁾. It has been shown that, in spite of certain difficulties caused by distortion of acoustic wave during propagation in the medium, spectral analysis is one of the most promising methods for characterization of AE phenomenon. However, due to the complexity of non-stationary AE signal there is still a great deal to be learned about the AE spectra. It can be achieved by new approaches to data processing, for example. The evolution of spectrum shape during deformation is usually described qualitatively in terms of typical frequencies or re-distribution of power density between low- and high frequency domains of spectrum. Spectral features are associated with the certain properties of AE sources⁽⁷⁾.

A fundamental investigation of fine structure of frequency spectra was reported in Ref. (8) with respect to the resonance of a sample or a transducer. A strong influence from the sample geometry, transducer properties and location on the resultant AE spectrum was shown. It is necessary to bear in mind, however, that

generally the spectral presentation of the process is equivalent the time presentation. Hence, any parameters used in a time domain contain implicit information about the frequency structure but this is often out of control after certain transformations of the initial signal. Thus, a clear interpretation of AE requires an understanding of contribution and the nature of different frequency components.

The purpose of the present study is to investigate the relationships between spectral AE parameters in order to find a reliable method of AE description in terms of spectral parameters. Copper and α -copper-aluminum single crystals of various orientations and copper polycrystals were used as model materials with known mechanical properties and partially known AE response.

II. Experimental

1. Specimen preparation

Polycrystalline copper of 99.999% purity has an average grain size of 1.8 mm and a thickness of 2.5 mm. This material was also used for preparation of copper and copper-3 at.% aluminum single crystals by growing in vacuum from seeds using the modified Briggman method. Crystallographic orientations of single crystals were determined within an accuracy of less than 0.5 degrees through the back reflection X-ray Laue method.

The specimens for the uniaxial tension tests were shaped by a spark erosion machine. Orientations of the tensile axis are shown in Fig. 1. The specimens were mechanically and electrolytically polished before annealing cyclically in vacuum at 920 K (30 min)-1170 K (30 min) for 24 h and cooled slowly to room temperature.

The specimens were loaded in tension with a constant nominal strain rate of 10^{-4} s^{-1} in an Instron type testing machine. The specimen parts containing the holes to be

Fig. 1 Orientations of the tensile axis of the single crystals tested.

Fig. 2 Frequency response of the AE transducer.

fit into the grips of a testing machine were preliminary loaded in compression in the direction perpendicular to the broad surface to eliminate possible plastic deformation of those parts and to reduce an undesired noise.

2. Characteristics of transducer

Experiments were conducted using a piezoceramic broadband sensor which frequency response is shown in Fig. 2. The certain non-linear properties of the transducer were designed in order to achieve a compromise between a sensitivity and a bandwidth.

3. Acoustic emission monitoring system

The simplified block diagram of the measuring system is shown in Fig. 3. A 10 bit analog-to-digital converter (ADC) of $\omega_d = 5$ MHz highest frequency is employed in order to provide a proper digital image of the electric signal which is taken from the output of the 20–2000 kHz bandpass filter following a low-noise broadband preamplifier MAX-1. This amplifier having the 40–60 dB continuously selectable gain in the 20–2000 kHz (± 2 dB) bandpass provides the peak-to-peak noise level less than $5 \mu\text{V}$. Unlike other similar commercial devices MAX-1 contains a built-in amplitude detector circuit with a time constant of 100 ms for a simple way of so-called “AE-level” or “envelope” (V_e) monitoring. Measurements of this parameter were done by a relatively slow 12 bit integrating ADC which is also connected through a

Fig. 3 AE apparatus.

multiplexor with the bridge-amplifier outputs of the load cell and the gage length meter.

The same data interface for AE and mechanical parameters provides a good synchronization with respect to time, strain and stress.

Experimental data were collected, stored and processed by the IBM PC computer using an original software. As IBM PC has a rather slow data accession rate via the CAMAC interface, some method of preserving the digitized emission while awaiting data transfer is required. This is achieved by interposing a 16 k Word (10 bit) fast Randomly Accessed Memory (RAM) between the ADC and the CAMAC bus interface. A capacity of memory allows to store the 10 bit data corresponding to a rather long single realization up to a duration of 3.2 ms with a sampling interval of $0.2 \mu\text{s}$. Such length of the record provides a superior resolution as for continuous as for burst emission. Moreover, the short time series of the individual bursts can be also recorded. Once digitized and stored signal can be examined in numerous ways.

The sensor was attached to the less deforming part of the specimen broad surface using an easily melted solder which ensure a reliable acoustic contact during the test (Fig. 3).

A total gain was of 72–75 dB. An ADC threshold was set slightly higher than the noise level. Several noise signals were measured during about 10 s just before the each test anticipating the further identification of the artificial noise signals that must be excluded from the analysis.

4. Signal processing

The standard digital Fast Fourier Transformation (FFT) gives a periodogram $I_v(\omega_k)$ for each individual pulse as follows:

$$V_k = \sum_{n=0}^{N-1} V_n \exp\left(-i \frac{2\pi kn}{N}\right);$$

$$I_v(\omega_k) = 2 \frac{h}{N} |V_k|^2, \quad (1)$$

where $h=1/2\omega_c$ is a sampling interval, $\omega_c=\omega_d/2$ is the highest frequency of the analysis; $T=Nh$, where N is the total number of points in the record. Such a single periodogram is not a consistent estimate of the power spectral density $G_v(\omega)$. Some methods involving various windowing and averaging procedures have been developed for improving this estimate⁽¹¹⁾ and successfully applied to AE in Ref. (4). In the present work a Daniel and a Tukey-Hanning spectral windows $W(\theta)$ ⁽¹¹⁾ were used to decrease the variance of the power spectral density function $h(\omega)$ estimate via following procedure:

$$h(\omega) = \int_{-\pi}^{\pi} I_v(\theta) W(\omega - \theta) d\theta, \quad (2)$$

where the Daniel rectangular window $W(\theta)$ is given as

$$W(\theta) = \begin{cases} M/2\pi, & -\pi/M \leq \theta \leq \pi/M \\ 0, & \text{otherwise,} \end{cases}$$

and the Tukey-Hanning window $W(\theta)$ is written as

$$W(\theta) = \frac{1}{4} D_M\left(\theta - \frac{\pi}{M}\right) + \frac{1}{2} D_M(\theta) + \frac{1}{4} D_M\left(\theta + \frac{\pi}{M}\right),$$

where $D_M(\theta)$ is known as ‘‘Dirichlet kernel’’ having a form

$$D_M(\theta) = \frac{1}{2\pi} \left\{ \frac{\sin[(M+1/2)\theta]}{\sin(\theta/2)} \right\}.$$

The window parameter M determines the degree of smoothing which is applied to the periodogram: the smaller M the greater the smoothing.

The spectral parameters such as the total energy E , the maximum power density $G_{\max}$, the effective spectral width W_{eff} , the median frequency f_{med} , central frequency f_c were numerically calculated after filtering and smoothing procedures. A Root Mean Square voltage V_{RMS} and a peak amplitude V_p were also defined from the digitized signal shape.

III. Results and Discussion

Typical time histories, periodograms and energy spectra for [110] oriented copper single and polycrystals are shown in Figs. 4 and 5. The marked differences can be seen between those spectra. Therefore, materials involved were considered separately. Although we shall exemplify the results only for copper single crystals, the same conclusions concerning to the correlation between some AE parameters can be drawn for all materials

Fig. 4 AE signal, Fourier spectrum and energy spectral density in the [110] oriented copper single crystal.

Fig. 5 AE signal, Fourier spectrum and energy spectral density in copper polycrystal.

tested.

It should be noted that the windowing is strongly recommended for the spectrum estimates. It can be seen that the Fourier spectrum calculated via eq. (1) and the energy spectrum obtained by eq. (2) are considerably different (Figs. 4 and 5). Calculating the variances for the periodogram as (Ref. (11))

Table 1 Estimate of relative standard deviation of energy spectra smoothed by different windows.

Smoothing window	Sample interval h (μ s)	Number of samples N	Relative standard deviation
None	0.2	4096	1
10 kHz Daniel	0.2	4096	0.77
10 kHz Daniel	0.5	4096	0.31
100 kHz Daniel	0.2	4096	0.08
100 kHz Daniel	0.2	1024	0.33
10 kHz Tukey	0.2	4096	0.58
10 kHz Tukey	0.5	4096	0.23
100 kHz Tukey	0.2	4096	0.06
100 kHz Tukey	0.2	1024	0.25

$$\text{var}\{I_v(\omega)\} = I_v^2(\omega) \left\{ 1 + \left[\frac{\sin(h\omega N)}{N \sin(h\omega)} \right]^2 \right\}, \quad (3)$$

and for the energy spectral density as

$$\text{var}\{h(\omega)\} \approx \alpha \times h^2(\omega) M / N; \quad (4)$$

$$M = \frac{2\pi}{h\Delta\omega},$$

we obtain the relative standard deviations of energy spectra smoothed by different windows as represented in Table 1. It is shown that a dimensionless constant α (eq. (4)) depends on the window shape: $\alpha=1$ for the Daniel window and $\alpha=0.75$ for the Tukey-Hanning window⁽¹¹⁾.

It becomes evident that the shape of the window is less important than the choice of the parameter M which controls the “width” $\Delta\omega$ of $W(\theta)$, variance and bias of the estimates. This result supplement those of Egle, Tatro and Brown⁽⁴⁾ who performed the same comparison between the so-called Barlett’s method of the power spectral density estimation and the rectangular windowing procedure.

The correlation fields for the AE spectral parameters in [110] oriented Cu single crystals are shown in Figs. 6 and 7 as a typical example. It can be seen that there are no simple correlations between any pairs of parameters. In other words, they are independent. The certain weak correlations exist between V_p and V_e as well as between f_{med} and W_{eff} . One can also say that while the effective width of spectrum is larger than 200 kHz the energy does not depend on it. It retains nearly constant. It is important that the energy weakly depends on the peak voltage and the AE-level. In some studies the squared AE-level measured by a device similar to that used here, is frequently associated with the AE energy E_e . The variance of such estimate seems to be too high. It should be noted that the RMS voltage computed from the digitized data shows the same magnitude of the energy E_{RMS} as the calculation of the area under the energy spectral density E_{spectr} as given by

$$E_{spectr} = \int_0^{\omega_{max}} G_v(\omega) d\omega \approx V_{RMS}^2 \Delta T; \quad (5)$$

$$V_{RMS} = \frac{1}{\Delta T} \sqrt{\int_0^{\Delta T} V(t)^2 dt},$$

Fig. 6 Correlation fields for spectral AE parameters.

Fig. 7 Correlation fields for spectral AE parameters.

with an obvious notation. From the calculations we have that $E_{spectr}/E_{RMS} = (1.0 \pm 0.2)$ while $E_{spectr}/E_e = (2.3 \pm 1.2)$. It means that the choice of the time constant of the ampli-

Table 2 Mathematical expectancies and standard deviations for spectral AE parameters.

Parameter	N	$V_{RMS},$ μV	$V_p,$ μV	$f_c,$ kHz	$G_{max},$ $(\mu V/kHz)^2$	$W_{eff},$ kHz	$f_{med},$ kHz	$E_{spectr},$ $\mu V^2 s$	$E_c,$ /10
Cu (poly)	754	6.1	28	128	96	110	530	2.6	2.2
Std.D.		1.4	12	36	28	45	124	1.8	1.2
Cu (sing)	702	6.8	65	136	143	160	448	6.2	2.7
Std.D.		1.6	67	111	154	85	118	3.4	0.9
Cu-Al	346	5.6	171	244	203	82	378	4.6	2.8
Std.D.		1.2	184	207	200	91	322	2.5	1.2

tude detector circuit was not suitable. We should note that it is difficult to suggest any physical arguments for the rule of the time constant setting a priori since AE is inherently a non-ergodic process when the averaging over the ensembles is not equal to the averaging over the time. One can recommend this simple method of the energy estimation only for the purely continuous emission. Otherwise a broadband spectral method should be utilized as a universal technique. The digital methods of the RMS voltage and energy estimations always can be used. The average values and standard deviations of parameters measured are shown in Table 2 for all the materials tested. The AE spectral parameters during plastic deformation demonstrate a large dispersion of magnitudes. This fact can be attributed to a variety of AE sources as well as to a hierarchy of their scales.

The results described above are closely linked to the general problem of spectrum characterization and are directed toward answering the question "How can an AE spectrum be described?" This problem should be divided into two parts. At first it is necessary to characterize a spectrum shape generally, since the shape itself is the most important attribution which is directly connected with the properties and behavior of the sources. For instance, a spectrum shape can be some times associated with one of the known spectral models which are shown in Fig. 8. These curves reflect an essentially different behavior of the collective sources. We have to bear in mind that AE always involves the movement of the large groups of atoms, dislocations, twins, etc., whose different behavior leads to the marked differences in the spectrum shape as is shown in Ref. (12). It should be also noted that with the use of a narrow band transducer, information about the spectrum shape is completely lost and the problem of source identification becomes too indefinite in general. Moreover, even when the source is known, the monitoring of its development by means of the unique narrow band component is rather ambiguous. Indeed, let us assume that during deformation (or any other external influence) the spectral density function changes as shown in Fig. 9 by arrows. Measuring a narrow band signal, one can conclude that the energy of the source is decreasing (Fig. 9(a)) or is nearly constant (Fig. 9(b)) while in fact it is increasing due to the changes in the shape of spectrum. Such a conclusions become partic-

Fig. 8 Model spectra (solid lines) and narrow band sensor response (dashed line). See comments in the text.

Fig. 9 Evolution of the Lorentz spectrum (solid lines) and narrow band sensor response. See comments in the text.

ularly dangerous in the engineering applications. Thus, the analysis of the energy re-distribution with respect to time⁽¹⁾⁽⁴⁾⁻⁽⁶⁾⁽⁸⁾⁽¹²⁾ seems to be much more advanced. The qualitative delineation of the spectrum shape can be supplemented by the set of considered above parameters in order to give a quantitative description. It is obvious that the parameters involved rightly respond to a variety of possible alternations of spectra. For example, a widening of spectrum (Fig. 7) can be determined through F_{med} or W_{eff} . The latter parameter is especially convenient for the Lorentz spectra $G(\omega) \sim \omega_0 / (\omega_0^2 + \omega^2)$ since W_{eff} is related to the shape parameter ω_0 as given by

$$W_{eff} = \frac{1}{G(0)} \int_{-\infty}^{+\infty} G(\omega) d\omega = \omega_0 \int_0^{\infty} \frac{d\omega}{\omega_0^2 + \omega^2} = \frac{\pi}{2} \omega_0. \quad (6)$$

IV. Summary

The following conclusion can be drawn from the investigation into the AE spectral parameters.

It becomes evident that the AE spectral parameters which have been analyzed above have no simple correlations between themselves. It means that they describe different aspects of the AE spectrum shape independently of one another. Hence it is necessary to consider at least a set of the above-mentioned parameters to the realistic characterization of spectrum as a whole. The minimum set recommended includes the maximum power (energy) density, the central frequency, the effective width of the spectrum or median frequency and the total power (energy). This approach to the signal processing provides the comparable and reliable results. It allows a uniform description of the AE pulse features for different materials and testing conditions.

Acknowledgements

The authors would like to thank Ministry of Education, Science and Culture, Japan for the financial support of the part of present work and for the scholarship to one of the authors (A.V.). We are also grateful to

Prof. A. Vikarchuk, Togliatti Polytechnic Institute (Russia) for his stimulating interest. The experiments themselves could not have been carried out without the assistance and collaboration of Dr. D. Merson and Mr. V. Patlan, Togliatti Polytechnic Institute.

REFERENCES

- (1) H. Hatano: J. Appl. Phys., **48** (1977), 4397.
- (2) W. Scharwächter and H. Ebner: Acta Metall. Mater., **38** (1990), 195.
- (3) G. Curtis: Non-destr. Test., **4** (1974), 82.
- (4) D. M. Egle, C. A. Tatro and A. E. Brown: Mater. Evaluation, **39** (1981), 1037.
- (5) L. J. Graham and G. A. Alers: Mat. Evaluation, **32** (1974), 31.
- (6) B. Woodward and R. W. Harris: Acustica, **37** (1977), 190.
- (7) D. Rouby, P. Fleishmann and C. Duvergier: Phil. Mag, **37** (1983), 671 and 689.
- (8) K. Ono and J. Ucisik: Mater. Evaluation, **2** (1976), 32.
- (9) S. H. Carpenter and C.-M. Chen: J. of Acoustic Emission, **7** (1988), 161.
- (10) V. S. Ivanova, Z. G. Fridman and E. G. Smirnov: Izv. Vuzov Metally, **6** (1974), 169.
- (11) M. B. Priestly: *Spectral analysis and time series*, vol. 1, Academic Press, N. York, (1981), p. 653.
- (12) A. P. Braginskiy: *Theoretical and engineering aspects of acoustic emission analysis of defect dynamics in solids*, Preprint IMF, N27, Kiev, (1986), p. 30.